THE APPLICATIONS OF VARIOUS STEELS.

Paper presented to the Institution, London Section, by L. W. Johnson, M.I.P.E.

Introduction.

THE number of steels which are available at the present time are so numerous that it is impossible in the scope of this lecture to do more than touch the fringe of the subject. It is therefore proposed to consider first the various elements which are usually found in steels and to describe briefly their effect. Then the different types of steels will be considered under various groups.

EFFECT OF VARIOUS ELEMENTS ON STEEL.

Carbon.

Carbon is found in varying amounts in all steels and in most structural steels is an essential constituent. It is added in amounts up to about 2.0 per cent. and forms a carbide of iron which hardens the iron and which may exist in different forms according to the content and heat treatment. The value of carbon lies in the fact that it enables a range of properties to be obtained by suitable heat treatment. If a steel containing carbon is heated it will be found that at a certain temperature (called the change point or transformation point) the carbon goes into solid solution which is also accompanied by a volume change. If the steel is cooled very rapidly this solid solution is retained at room temperatures and produces a hard and relatively brittle material in the case of medium and high carbon steels. On re-heating or tempering, a lowering of the hardness is produced together with an increase in the ductility. Slow cooling on the other hand from above the change point produces in the case of low carbon steels a soft and ductile material. The change of a carbon steel at the change point from one state to another takes place at a definite rate and obviously if we wish to preserve that state we must cool the steel at a rate which is greater than the rate at which the change takes place. In the case of carbon steels this rate of change is very rapid which therefore necessitates a very rapid quench such as is obtained by cold water or iced brine. This question of the speed of quenching is of very great importance in heat treatable steels as will be seen later.

November 4th, 1932. (Vol. XII, No. 4, April, 1933).

Silicon.

Silicon is present in all steels as it is used as a deoxidiser owing to its great affinity for oxygen and is usually kept below 0.3 per cent. For structural purposes it has very limited uses such as for springs where the content may vary from 1.0 to 2.0 per cent., and for electrical transformers where high electrical resistance is desired to reduce eddy current losses, and the content varies from 2.5 to 5.0 per cent. All the commercial silicon steels are pearlitic when slowly cooled.

Manganese.

Manganese is used in the manufacture of practically all steels, both as a deoxidiser and also to unite with the sulphur present in the steel, in preference to iron sulphide which, by forming around the grain boundaries, causes brittleness. In order to be on the safe side excess manganese is added so that there is found in structural steels between 0.3 per cent. and 0.9 per cent., and in tool steels about 0.25 per cent., where it is desirable to keep the manganese content low. It is also used in structural steels in the range 1.0 to 2.0 per cent. and 12 to 14 per cent., the latter being austenitic with abrasion resisting properties. Manganese hardens steel by both forming carbides and dissolving in the iron constituent.

Nickel.

As an alloying element nickel is unique in that it is the only common metal which is soluble in iron and steel in all proportions. It does not form carbides and is present in steel entirely dissolved in iron (ferrite constituent) which it toughens. It also increases the strength and hardness of the steel, and by heat treatment greatly enhanced properties are obtained. Nickel lowers the change point, refines the grain and restricts grain growth at high temperatures. It also slows up the rate of change at the transformation point, and this allows a less drastic quenching medium to be used than is necessary in the case of carbon steels or, alternatively, it intensifies the hardening power. These properties enable heat treatment to be more foolproof and also allow the beneficial effects of heat treatment to penetrate deeper into steel of large section. Increasing the content of nickel produces three types of steels, pearlitic, martensitic, and austenitic. Steels of the first group containing up to 6.0 per cent. of nickel find very extensive use for structural purposes, the second group has a very limited range, and the third group (25 per cent. nickel and over) produces some steels which have very interesting properties which will be discussed later. Nickel does not oxidise in the furnace.

Chromium.

Chromium is present in steel practically entirely in the form of carbides, and has a hardening and strengthening effect on steel.

It raises the transformation point and, by increasing the viscosity of the solid solution slows up the transformation, as does nickel, thus producing greater depth hardening. Chromium oxidises during the steel-making process. Chromium is present in structural steels in the range from 0.25 to 2.0 per cent., and also in the range 12.5 to 14 per cent., which constitutes the original stainless steel. Nickel and chromium are very often used in combination as each complements and emphasises the other, thus providing structural steels which possess high strength coupled with excellent toughness and resistance to shock and fatigue. In the higher percentages these two elements form the basis of corrosion and heat-resisting steels.

Molybdenum.

Molybdenum acts in steel principally through carbide formation and is added for strength and toughness. It raises the transformation point and responds very readily to heat treatment, more especially when used in conjunction with other elements such as nickel and chromium, when it enables a greater penetration of the beneficial effects of heat treatment to be obtained in large sections. It does not oxidise in the furnace, and tends to produce free scaling properties. Molybdenum is generally used up to about 0.6 per cent.

Vanadium.

Vanadium is present in steel as carbides, and as it oxidises very easily is used as a scavenger. In ordinary structural steels it is used up to 0.25 per cent. and about two per cent. is used in high speed tools. It responds to heat treatment, and tends to refine the grain.

Tungsten.

Tungsten acts through carbide formation, and greatly increases the fineness of the structure. It is chiefly used in connection with tool steels from about 1.0 per cent. up to 20 per cent., and at the higher percentages is more generally associated with other elements such as chromium, vanadium, cobalt, etc. Steels containing about 5.0 to 6.0 per cent. of tungsten are also used for magnets.

Cobalt.

Cobalt produces in steel properties somewhat similar to those obtained with nickel, but its main uses have been in connection with permanent magnets and also in conjunction with tungsten and chromium for super high speed steels. In the latter case it enables a cutting tool to retain its cutting edge for a much longer period than in the case of ordinary high speed steels.

Aluminium.

Aluminium was up to a short time ago used solely as a deoxidiser but recently it has been found to have beneficial effects in connection

with steels which are hardened by means of nitrogen. For these steels it is used up to 2.0 per cent.

CARBON STEELS.

Wrought iron and cast iron were used for constructional purposes for several centuries, but about seventy years ago the advent of the Bessemer and the Open Hearth processes enabled carbon steels to be produced on such a scale that they quickly replaced the wrought iron which had been hitherto used and so provided the engineer with larger scope. At the present time it is true to say that carbon steels constitute by far the largest portion of steel production. Although, at one time they were almost universally used, apart from tool steels, this is not so to-day as modern progress, by demanding more and more from materials, has brought about the development of alloy steels.

As has been seen previously, variations in the carbon content produce differences in the mechanical properties which will give a range varying from very mild to extremely hard steel. At the same time increase in hardness is accompanied by decrease in ductility and consequently, the choice of any particular steel for a particular application will naturally depend on the properties required and in very many cases it is essential to compromise.

Carbon steels can be conveniently grouped as follows :—

(*a*)	Carbon	content	below	0.15			per cent.
(*b*)	,,	,,	between	0.15	and	0.25	,,
(*c*)	,,	,,	,,	0.25	,,	0.35	,,
(*d*)	,,	,,	,,	0.35	,,	0.45	,,
(*e*)	,,	,,	,,	0.45	,,	0.55	,,
(*f*)	,,	,,	,,	0.55	,,	0.90	,,
(*g*)	,,	,,	,,	0.90	,,	over	,,

Group (*a*) comprises very mild steel which is used for tubes and similar applications to wrought iron, and for case-hardening.

It is probably true to say that by far the greatest tonnage of carbon steels goes into group (*b*) which comprises steel rather loosely termed "mild steel," which possesses a tensile strength of 26 to 33 tons per square inch and which is generally used in the "as rolled" condition. Its main applications, in the form of bars, plates and sections, are for general constructional work such as bridges, ships, steel buildings, and the like, and as forgings for marine shafting, crankshafts, and other moderately low tensile components.

Mention may also be made of "free cutting steels," in which easy machinability is obtained by increasing the sulphur and phosphorus contents to 0.10 per cent. and over, thereby producing a steel with lack of toughness, so that the chips easily break away. It is important to stress the fact that toughness is not usually associated with ease of machining and of course, for many components it is important that the steel shall be tough.

Group (*c*) provides a higher tensile range and is naturally used where conditions preclude the use of the ordinary mild steel. In the case of group (*d*) tensile strengths of from 35 to 45 tons per square inch are obtained. This type of steel is very often used in the "normalised" condition, but by hardening and tempering it is possible to obtain improved properties. This steel forms the basis of a 1.0 per cent. nickel steel which will be referred to later, and is used for such components as low stressed crankshafts, axles, etc. Steel of the type (*e*) is used fairly extensively for gears, aero engine cylinders and occasionally for brake drums. In group (*f*) will be found steels used for various types of springs, and rails. Groups (*f*) and (*g*) comprise various types of cutting tools.

MEDIUM ALLOY STEELS.

Modern engineering requirements demand increasing strength whilst retaining toughness and ductility and the fact that the amount of ductility which it is possible to obtain from carbon steels is somewhat severely limited by the tensile strength has naturally led to the development of alloy steels which do not possess these drawbacks. At the same time carbon steels have other disadvantages in that it is usually necessary to water quench them to obtain the best properties and this leads to cracking and distortion, also since the rate of quenching must be very high in order to prevent transformation at the change point, it will be obvious that, in the case of large masses which must of necessity cool slowly, the rate of cooling will not be sufficient to retain the correct structure. In other words, the beneficial effect of heat treatment does not penetrate very deeply. This is known as "mass effect" and nickel, chromium and molybdenum either singly or in combination have a beneficial effect in this respect.

This question of ductility with strength is illustrated in a striking manner by Mr. H. Brearley* in the following table in which mechanical properties are given for a carbon and three per cent. nickel steels when heat treated to give the same tensile strength.

*"*The Case-Hardening of Steel*" by *H. Brearley, p.104.* (*Longmans, Green & Co.*).

CHEMICAL COMPOSITION.

	Carbon Steel.	Three per cent. Nickel Steel.	
Carbon ...	0.33	0.33	per cent.
Silicon	0.15	0.13	,, ,,
Manganese ...	0.63	0.63	,, ,,
Nickel	—	3.28	,, ,,

MECHANICAL TESTS.

	Yield Point.	Maximum Stress.	Elongation per cent.	Reduction of Area per cent.	Izod ft./lbs.
	tons/sq	. inch.			
HARDENED AND TEMPERED.					
Carbon Steel	—	52.8	16.0	43.2	10,11
Three per cent. Nickel Steel ...	43.2	52.9	25.0	64.9	100,104

Perhaps the most satisfactory way in which to deal with low alloy steels will be to classify them according to tensile strength, as follows :—

Steels having a tensile strength of less than		40	tons per sq. in.
,, ,, ,, ,, ,,	between	40 to 54	,, ,, ,, ,,
,, ,, ,, ,, ,,	,,	55 to 75	,, ,, ,, ,,
,, ,, ,, ,, ,,	over	100	,, ,, ,, ,,

(*a*) Tensile strength of less than 40 tons per square inch.

This group comprises nickel steels, nickel-manganese and manganese steels. There are many components which because of their size and other considerations can only be given a simple heat treatment such as " normalising " (i.e., heating to about 860°C. followed by cooling in air), and so use is made of the refining and toughening effect of nickel. Instances of this are the use of nickel steel plates for locomotive boilers which enable increased pressure to be adopted without increase in weight and also are not subject to the " ageing embrittlement " to which cold worked carbon steels are liable ; also the 3.5 per cent. nickel steel chassis frames for commercial vehicles ; low carbon 2.0 per cent. nickel steel for locomotive components where it is important to have an increase in toughness and resistance to shock coupled with a moderately low tensile strength.

(*b*) Tensile strength of 40 to 54 tons per square inch.

In this category are found 3.0 per cent. nickel, which is a very extensively used steel, 1.0 per cent. nickel, 1.0 per cent. manganese, and 1.5 per cent. manganese-molybdenum steels and in general they are used in the heat-treated condition. The addition of 1.0 per cent. of nickel to the 0.35/0.45 per cent. carbon steel has resulted in an improved yield point and toughness as indicated by the more consistent results obtained in the Izod impact test ; and so this steel has become very popular in the automobile industry for the lower stressed components. A further modification of this steel is the combination of 1.0 per cent. each of nickel and manganese which provides a material which does not suffer from the variable behaviour associated with the use of about 1.5 per cent. of manganese when used alone. This steel will easily satisfy the requirements of the British Standards Specification S.76, with an oil quench, and moreover, will provide good Izod values as will be seen in Table I. They will conform to the following British Standard Institution Specification :—B.S.5005/401, B.S.5005/203, B.S.5005/204, 2S6 and S76. The applications of this group are very numerous, and mention may be made of bolts and studs, crankshafts, axles, gears and gear wheel rims, alternator rotors, and shafting for general engineering.

TABLE I.

HARDENED AND TEMPERED ALLOY STEELS.

Tensile Range	Chemical Composition %					Mechanical Properties.						British Standards. Institution Specification No.
	C	Mn	Ni	Cr	Mo	Yield Point tons/ sq. in.	Maximum stress tons/ Sq. in.	Yield Ratio p.c.	Elongation p.c.	Reduction of area pc.	Izod. Impact ft.-lbs.	
40–54	0.40	0.5	1.0	—	—	25.2	42.4	59	28	62.0	45	B.S.5005/204
	0.38	1.0	1.0	—	—	30.7	45.3	67	27	61.5	45	S.76
	0.30	0.5	3.0/ 3.5	—	—	42.6	49.7	85	26	65.5	75	B.S.5005/401
55–75	0.40	0.5	3.5	—	—	48.3	55.6	87	23.0	63.5	48	S.69
	0.30	0.5	3.5	0.7	—	55.4	60.7	91	22.5	63.0	72	3 S.11
	0.30	0.5	3.5	0.7	0.2	59.0	64.8	91	21.0	61.0	65	do.
	0.25	0.5	3.0	1.2	0.2	64.2	70.1	91	20.0	59.5	55	S.65
100 and over	0.38	0.5	1.5	1.0	—	94.5	110.3	86	12.0	35.0	15	B.S.5005/503
	0.30	0.5	4.25	1.25	—	93.9	108.8	86	12.5	40.3	19	2 S.28
	0.30	0.4	3.40	0.6	0.2	88.0	105.4	83	11.0	3.30	18	

(*c*) Tensile strength of 55 to 75 tons per square inch.

The steels most generally employed for this group are $3\frac{1}{2}$ per cent. nickel, nickel-chromium and nickel-chromium-molybdenum according to the particular application and they conform to the following British Standard Specification :—S.69, B.S.5005/601, 3.S.11, S.65, and S.81. These steels are characterised by high tensile strength coupled with excellent toughness and ductility and also with very good depth hardening properties. Typical tests are given in Table I, and in Diagram A, is shown the effect of tempering at different temperatures, a fully-hardened $3\frac{1}{2}$ per cent. nickel-chromium-molybdenum steel. This diagram is typical of the different nickel-chromium and nickel-chromium-molybdenum steels in this group. There will, of course, be variations in actual figures from steel to steel. Although a limit of 75 tons per square inch has been fixed for this group, it is possible to obtain tensile strengths with some compositions, of 80 tons per square inch and over coupled with high Izod values. Mention may be made of "temper brittleness" to which some nickel-chromium steels are subject and which manifests itself by somewhat low Izod values when the steel is slowly cooled from or through the range of about 325 to 450°C. This can be obviated in practice by cooling in water or oil after tempering or if rapid cooling is not practicable then the addition of a small percentage of molybdenum will prevent "temper brittleness." This group of steels finds very extensive uses in the automobile, oil engine and aircraft industries for such components as crankshafts, connecting rods, drive axles, struts, tubes, gears, highly stressed shafts and high tensile bolts and flanges for steam plants.

(*d*) Tensile strength of over 100 tons per square inch.

Oil-hardening and air-hardening nickel-chromium and nickel-chromium-molybdenum steels are used for providing a tensile strength of over 100 tons per square inch. The air-hardening steel which conforms to the British Standards Specification 2.S.28 is really quite a remarkable steel when it is considered that by cooling in air from 830° C. followed by tempering at 200° C. a tensile strength of over 100 tons per square inch is obtained together with quite good toughness and ductility. The main value of air-hardening lies in the relative absence of distortion and consequently this steel is suitable for many types of gears, as well as axles and spars and tubes for aircraft.

CASE-HARDENING STEELS.

In order to resist wear it is necessary to have hardness, and since extreme hardness in steel is always accompanied by brittleness it is not desirable to make components of one uniform composition. The problem of obtaining toughness, coupled with surface hardness,

55 TON STEEL

Tempering curves for nickel-chromium-molybdenum steel

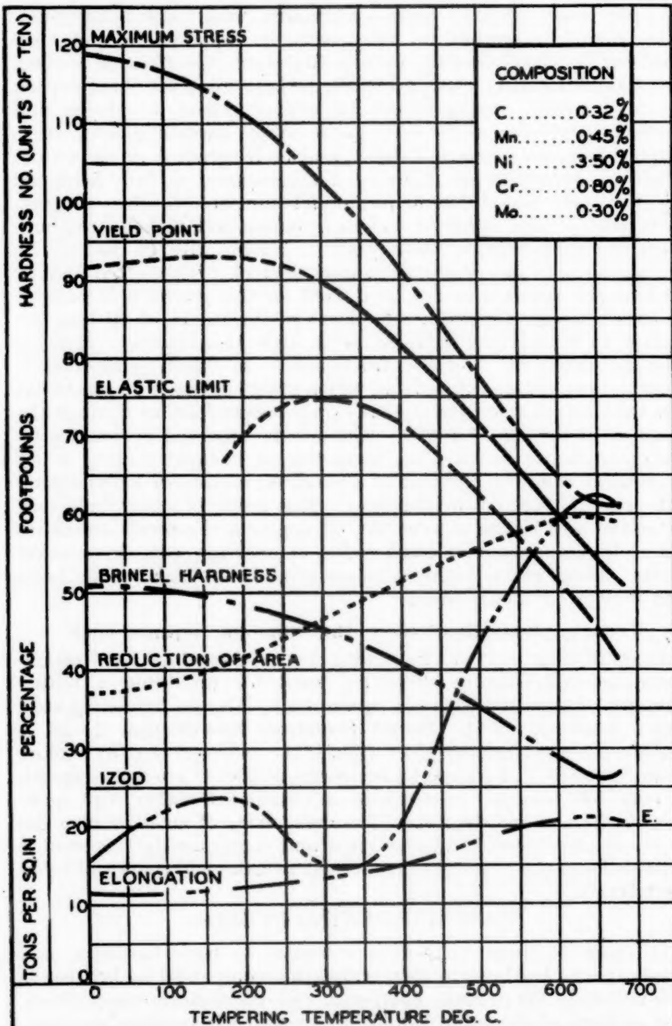

DIAGRAM A.—1¼-in. diameter bars quenched in oil from 830°C.

has been solved by taking a low carbon steel which is comparatively soft and tough, and introducing into its surface sufficient carbon to produce a hard layer, by heating the steel at about 900° C. in contact with a suitable carburising compound for several hours.

For many years carbon steel containing less than 0.2 per cent. of carbon was used for this purpose, but as in the case of the ordinary type of structural steels it soon became necessary to strengthen up the core of the material in order to enable heavier loads to be carried without increasing the depth of case. This resulted in the development of nickel, nickel-chromium, and nickel-chromium-molybdenum steels, which in turn gave progressively stronger core strengths as will be seen from the Tables II and III. In connection with case-hardening, the actual operation of carburising and subsequent heat treatment is of great importance.

When a carbon steel is heated for some time at 900° C. there results very considerable grain growth which produces lack of toughness. Consequently, in the subsequent heat treatment it is essential first to refine the core by heating up to 900° C. followed by quenching, and then to harden the case by heating it up to its correct hardening temperature (about 770° C.) followed by quenching. We have previously seen that in the case of carbon steels it is essential to have quite drastic quenching in order to retain the hardness. Consequently, this fact, coupled with the double heat treatment is costly and also tends to produce warping and cracking.

The effect of nickel is such that it enables sufficient hardness to be obtained in the case by oil quenching, and since this is less drastic, there results considerably less risk of distortion. It has also been found that since nickel resists grain growth, the refining portion of the heat treatment can be omitted and perfectly satisfactory results can be obtained by a single quench. It is not, therefore, surprising to find that for the ordinary 3.0 per cent. nickel steels it is almost the universal practice in the automobile trade to adopt single quenching. For single quenching purposes it is the general practice to use a steel containing not less than 3.25 per cent. of nickel.

It may not be out of place at this stage to mention the nitriding process which is not the same as case-hardening. It was found by Dr. Fry, of Messrs. Krupps, that he could harden special steels by subjecting them to ammonia gas at about 500° C. for periods up to ninety hours. This produces a very hard case of the order 1,000 Vickers' diamond hardness number, and does not require any subsequent heat treatment. It has been found that for most gears the case is somewhat too brittle, and also it does not lend itself to the initial " bedding-in " but, for applications where materials have to run dry, this process is giving satisfactory results. Typical applications for case-hardening steels are for gears of all kinds.

TABLE II.

Type of Steel.	Chemical Composition Per Cent.				British Standards Institution Specification
	C.	Mn.	Ni.	Cr.	
Carbon	0.14	0.65	—	—	2 S.14
Three per cent. Nickel	0.14	0.50	3.30	0.10	3 S.15
Five per cent. Nickel	0.14	0.35	5.25	0.10	S.83
3½ per cent. Nickel-chromium	0.12	0.35	3.45	0.80	—
4½ per cent. Nickel-chromium	0.16	0.40	4.25	1.25	S.82

TABLE III.

Steel.	Heat Treatment.			Mechanical Tests.				
	Refine	Harden	Temper	Y.P. tons/	M.S. sq. in.	E. p.c.	R.A. p.c.	Izod ft./lbs.
Carbon	900°C. O.Q.	780°C. W.Q.	—	22.5	34.7	32.0	63.5	78
Three per cent. Nickel	860°C. OQ.	770°C. O.Q.	—	40.3	53.0	22.0	51.0	62
	—	770°C. O.Q.	—	38.0	51.3	21.5	51.0	60
Five per cent. Nickel	860°C. O.Q.	770°C. W.Q.	—	45.2	61.2	17.5	47.0	45
	830°C. O.Q.	760°C. O.Q.	—	57.0	69.3	19.0	52.5	48
3½ per cent Nickel-chromium ...	830°C. O.Q.	770°C. O.Q.	—	48.2	60.5	19.0	50.5	50
4¼ per cent Nickel-chromium ...	830°C. O.Q.	760°C. O.Q.	160°C.	76.0	88.2	13.0	42.0	38

CORROSION RESISTING STEELS.

The last few years has witnessed a large development both in the various kinds of corrosion resisting steels and in their applications. The earliest application was for cutlery, and the steel used contained about 13 per cent. of chromium, and can be hardened by heat treatment. Whilst this type of steel has good corrosion resistance in certain fields, it has certain drawbacks which limit its sphere of usefulness. For instance, it is necessary to use such steels in the fully hardened and polished condition to obtain the best resistance to corrosion. To a certain extent the sphere of usefulness has been extended by varying the carbon content, increasing the chromium content and the addition of small amounts of other elements, for example the steel containing 18 per cent. chromium and 2.0 per cent. nickel possesses improved corrosion resistance and is finding extensive use for aircraft fittings and spars.

The addition, however, of large amounts of nickel has been found to result in a series of austenitic nickel-chromium steels, which both possess superior corrosion resistance, which is applicable in a very large number of fields, and are also better from the point of view of fabrication than the straight chromium type. The most commonly used steel of this type contains about 18 per cent. chromium and 8.0 per cent. nickel and a low carbon content. In order, however, to meet special conditions, the percentages of nickel and chromium may be varied, for example an increase in the nickel content improves the workability. On the other hand small percentages of other elements such as molybdenum, tungsten silicon, copper, and titanium may be added. These austenitic nickel-chromium steels are available in all the usual forms, and in Table IV figures are given showing the mechanical properties which may be expected.

Mention should also be made of a trouble which has been experienced and which has been generally called " weld decay." Holding the austenitic nickel-chromium steels in the temperature range of 600° to 750° C. causes an alteration in structure which tends to produce brittleness and, in the presence of a corroding medium, enables intercrystalline corrosion to occur, with consequent loss of ductility, resulting in an embrittled material. This condition has been chiefly encountered after welding, where it is obvious that at a short distance from the weld there will be a region which has been in the above temperature range. It is possible to overcome this trouble by subsequently heating the steel to a temperature of 1,050° to 1,150° C. (the exact temperature depends on the particular composition of the steel), followed by rapid cooling. As this operation is not always possible in the case of large and complicated parts, research has shown that the trouble can be, and is overcome, by the addition of other elements such as tungsten and titanium, or more careful control of existing elements, in the steel, and several

TABLE IV.

CONDITION.	Proof Stress (0.5 per cent.) tons/sq. in.	Max. Stress tons/sq. in.	Elongation per cent.	Reduction of Area per cent.	Izod Impact ft./lbs.
Fully softened ...	12 to 25	35 to 55	45 to 70	45—75	95 to 115
Bright drawn bar ...	25 to 45	50 to 65	30 to 50	35—60	50 to 100
Cold rolled strip ...	35 to 60	55 to 70	10 to 40	—	—
Wire, cold drawn ...	—	90 to 110	—	—	—
Castings	12 to 25	35 to 50	10 to 20	—	—

patents have resulted. A special test has been devised to test the immunity of these steels from weld decay by immersion in a boiling solution of copper sulphate acidified with sulphuric acid, and in this connection, it must be stated that the test should be kept in its proper perspective from a corrosion resisting point of view. Since these steels have a very wide range of resistance to corrosive media it naturally follows that they also have a wide range of applications amongst which are chemical plant, including nitric acid plant, processes involving nitration, digestion of paper pulp with sulphite liquor, architectural including shop fronts, motor car fittings such as radiator shells, coaming and beading.

HEAT-RESISTING STEELS.

In order that a metal or alloy may be suitable for use at elevated temperatures it must possess two important properties: (1) Resistance to oxidation and to scaling at elevated temperatures; (2) Retention of strength at elevated temperatures. Other factors of importance, depending on the type of application for which material is required, must naturally be considered. For electrical purposes, the specific resistance and temperature coefficients are important; for constructional units coefficients of expansion must be considered; for many furnace applications resistance to penetration by products of combustion is required. The two first mentioned properties, however, are essential in practically all applications. Both high chromium and high nickel high chromium steels are used for purposes of heat resistance. The actual compositions cover a fairly wide range, but the chromium content may vary from about 10 to 30 per cent. and the nickel from 7.0 to 35 per cent. Small percentages of silicon and tungsten are also very often present in varying amounts up to 3.0 and 6.0 per cent. respectively.

The straight chromium steels will resist sulphurous atmospheres quite well up to temperatures of about 950° C., but as these steels are somewhat weak and brittle at these temperatures as well as at ordinary temperatures, it is usual to use a nickel-chromium heat-resisting steel if any stress is involved, such as in the case of valve steels for aero engines and high efficiency automobile engines, slicer links in furnace conveyors, etc.

The nickel-chromium heat-resisting materials are in what is known as the austenitic condition, i.e., no matter from what temperature they are quenched, there is no possibility of any hardening whatever taking place. This is a decided advantage when the steels are used for parts which are subjected to alternate heating and rapid cooling, as no hardening, and consequently no brittleness, will occur, also, since there is no critical point with its accompanying volume change, the liability of warping and cracking which is bound to result if an ordinary steel is continually rapidly cooled,

is considerably minimised. Also the adherent protective oxide layer is not broken. If the steel is required in a higher tensile condition this can only be achieved by cold work, the extent of which naturally varies in accordance with the size of the part being worked. It should be pointed out, however, in this connection, that heat treatment after forging has a softening effect and, while it is stated that the hardness is scarcely affected up to about 800° C., the effect of higher temperatures is to produce increasing softening, the maximum softness being obtained by air cooling from a temperature of about 1,050° to 1,150° C.

The heat-resisting nickel-chromium steels are available in all the usual forms, and in the tables V, VI and VII are given particulars of the mechanical properties of these steels. The applications of heat-resisting steels include exhaust valves of internal combustion engines, high pressure reaction vessels, slicer links, recuperators, retort tubes, locomotive fire box doors, and baffles.

TOOL STEELS.

A considerable range of tools are made from carbon steels having a carbon content of 0.65 per cent. and over. As has been previously mentioned, an increase in the carbon content results in harder material at the expense of ductility. Consequently, the lower carbon content will be used for those tools which do not require a very sharp cutting edge, but which must withstand hard usage, whereas the steels at the other end of the range will be used for such tools as files and razors.

Whilst carbon steel turning tools have and are giving satisfactory service under certain conditions, nevertheless, they are open to two disadvantages, the first being difficulties encountered in heat treatment, and the second being that they will not retain a cutting edge if the temperature becomes at all elevated. By using such elements as tungsten, chromium, vanadium, cobalt, etc., the functions of which have already been discussed, many improvements have been effected. There are so many different alloy tool steels available at the present time that it is not possible in the scope of this paper to do more than indicate a few of the uses.

Manganese in general is kept very low except for oil quenching, non-deforming tools when it is of the order of 1.0 per cent. Plain carbon, chromium, tungsten, nickel and nickel-chromium steels are used for chisels and it may be of interest to mention that in the case of the nickel steel chisels these are simply quenched in oil and the cutting edge can be dressed with a file. The application of cold work, however, immediately breaks down the tough and relatively hard sustenitic-martensite structure of the cutting edge into very hard martensite which cutting edge since it is backed up

TABLE V.

TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE OF HEAT RESISTING STEELS.

FORM.	Yield Point tons per sq. in.	Max. Stress tons per sq. in.	Elong. per cent.	Red. of Area per per cent.	Izod ft./lbs.	Brinell Hardness No.
FORGED.						
High Tensile Condition	30–38	55–62	40–30	46–38	30–40	220–280
Fully softened ...	24	49	32	45	50	212
CASTINGS	30	48	15	—	—	220–280

TABLE VI.

HIGH TEMPERATURE PROPERTIES OF A NICKEL-CHROMIUM HEAT-RESISTING STEEL.

TEMPERATURE of Test °C.	SHORT TIME TENSILE TESTS Max. Stress tons/sq. in.	Elongation per cent.	Limiting " Creep Stress " tons sq. in.
15	45.9 45.8	34.5 33.5	
600	34.7 33.1	22 22	11
700	25.1 24.1	21 20.5	6
800	17.3 17.2	39*	2

*Fractured at gauge mark.

by a tough " core " avoids many of the troubles of the ordinary carbon steel chisel.

Tungsten is a very useful element and whilst it is present, generally as 14 or 18 per cent. in high speed steels, it is also found in wire-drawers die steel usually between five and 10 per cent., and in small amounts in various carbon tool steels, dies and back-saw blades. With regard to the fairly recent developments of special materials made of tungsten and other carbides and also super high speed steels the author feels that many of the members present are far more qualified to speak than he is as to the question of the ultimate applications of these two types of alloy tools.

MISCELLANEOUS STEELS.

Manganese steel containing about 13 per cent. of manganese and just over 1.0 per cent. of carbon is in the austenitic condition and is relatively soft. If, however, it is subjected to impact work hardening results, a very hard surface is produced which will provide excellent resistance to abrasion.

It must be kept in mind that it is essential for the abrasive conditions to be such that the necessary work-hardening will occur. This steel finds applications for crushing and breaking down rock

TABLE VII.

TENSILE TESTS AT HIGH TEMPERATURES.*

	Maximum Stress—Tons Per Square Inch.							
Steel.	600°C.	650°C.	700°C.	750°C.	800°C.	850°C.	900°C.	950°C.
Three per cent. Nickel Chrome	34.0	23.6	13.5	11.2	9.2	6.9	4.5	—
Stainless Steel	24.2	17.3	10.2	8.0	6.1	5.6	7.9	—
Silicon Chrome	42.0	34.5	25.3	17.8	10.7	7.2	3.9	3.0
Chrome Steel	36.5	30.0	19.0	13.0	7.0	7.2	7.3	5.2
Cobalt Chrome	45.0	30.5	24.8	13.6	10.0	5.8	8.1	6.0
High Speed Steel	41.0	26.6	21.3	16.8	9.8	7.7	8.5	5.6
High Nickel Chrome ...	42.6	38.3	33.8	28.6	24.0	19.4	15.0	12.5

*P. B. Henshaw,—" Valve Steels," Jnl. Roy. Aero. Socy., March, 1927, No. 195, vol. 31, pp. 187-217.

and ballast and also for dredging. Where the conditions are not sufficient to produce work-hardening such as in the case of sand and limestone, chromium steel is used and if toughness is required as well as hardness then special nickel-chromium-molybdenum steel is adopted.

The nickel-iron alloys provide an interesting series as by varying the nickel content quite a large variation of the coefficient of linear expansion can be obtained. When about 36 per cent. of nickel is present the coefficient of expansion is of the order of 0.0000015 per °C. (ordinary steel is 0.000012 per °C.), and use is made of this very low expansion for adjusting the expansion of the skirts of aluminium pistons and of aluminium cylinder heads bolted on to steel cylinders ; rheostats for controlling temperature. The addition of about 12 per cent. of chromium to this material results in an alloy known as Elinvar which has a constant modulus of elasticity over the temperature range usually met with under ordinary atmospheric conditions and consequently finds applications for springs of accurate instruments. 25 per cent. nickel steel which is austenitic is non-magnetic and is naturally used in the electrical industry.

Discussion.

Mr. Ping : In opening the discussion on the range of steels we have heard of to-night, I shall confine myself to asking one or two questions. We engineers are always trying to do things faster and faster, and I was interested in a point mentioned quite early on as to the introduction of phosphorus in low carbon steels for the purpose of obtaining free cutting qualities. We like high speed due to those qualities, but what would be the effect on the final product in, for instance, the component parts of a driving chain? Would you as a consequence of the introduction of phosphorus get cracking in the case-hardening or would you get a less wearing quality?

Going to quite another subject. About 3½ years ago I introduced the combined resources of the people whom the lecturer has mentioned into a very large factory to see in what connection they could offer me some sort of stainless steel to overcome the question of corrosion by sulphuric acids in various strengths, hypo in various strengths and liquors of that sort. I am sorry to say that they turned down practically every proposition but, as the lecturer said, the progress made in the production of steels for new uses has been very rapid. Ten years ago stainless steel was entirely confined to cutlery manufacture, but great strides have been made, and I think probably since the occasion I have referred to they have found some stainless steels that would serve. I would ask if that is correct. Another point of interest to me particularly is that about six years ago I met Dr. Fry—who has been referred to by the author—and who was experimenting on nitriding steel. Taking driving chains as my instance, is it suggested that as a result of his work such steel could be usefully employed instead of ordinary case-hardened carbon steels?

Mr. Johnson : I think in the case of the free cutting steels that it would be inadvisable to use them for case-hardening for chains especially if the stressing was rather high. You would probably get trouble with flaking of the case and might also get grinding cracks apart from the lack of toughness associated with free cutting steels. With regard to the stainless steel, I am afraid that in the case of sulphuric acid, they are not very much forward. Some of the high nickel and chromium steels certainly resist it better than ordinary steels but they are still attacked. In the case of hypo, it is safe to say that they can resist that satisfactorily. In the case of the nitriding for the driving chains, the point to bear in mind is the fact that the case is very hard and also very brittle. In the case of gears I think it is found that in spite of all

precautions taken there are slight unevennesses on the steel, and you must have a certain amount of ductility there to allow for bedding-in. In the case of the nitrided steel as it is so hard it tends to resist that bedding-in and consequently you get the loading concentrated on a point which starts a fatigue crack. That is how I look at it, and I feel the same about driving chains; it all depends on the fit and on the stress and on how much toughness is required. Some chains which are probably of slow motion and large sections might be satisfactory. I believe nitrided steels are being used very satisfactorily in certain equipment in connection with cement manufacture.

Mr. W. Puckey: Mr. Johnson mentioned in the course of his lecture the question of fabricated aeroplane tubes. In an aeroplane, the lower the horse-power the better the thing is from the efficiency point of view; and there again from the point of view of economics one must necessarily use the steel of higher tensile properties, and one is rather restricted in one's steel from that point of view. Again, taking a special piece of mechanism such as is used in stone-crushing, one is restricted: one can only use such steel as manganese for the jaws of the crushing mechanism, but there are thousands of parts, mechanisms, implements, etc., on the market at the present time where one is not restricted and where the weight factor does not enter into the matter. When does it pay to use high tensile steels and when does it not? Where does the change-over come? There must be one somewhere, and it strikes me that it is rather an involved problem in those cases because not only have you to take the initial cost into account, but you must count the differences you are likely to get in the machining costs, and I should very much appreciate any information or any more light that could be thrown on this subject. As regards tubing: it has for some years been a very difficult problem for production engineers to screw-tap satisfactorily. It always has a tendency to tear badly and the thread becomes very ragged indeed. I am rather interested at the moment in tubing, and as far as I am aware there has been a general classification of tubing in recent years as Class A and Class B. I would like Mr. Johnson to let me know whether it is possible to get tubing in practically any tensile characteristics and also whether he can throw any light on this question of tapping of tubing or the general screwing of it. Thirdly, most members of the Institution will know that the particular subject for discussion this year is standardisation. I have felt for some considerable time that the steel industry, and, of course, the engineering industry, suffers from an embarrassment of riches. You get thousands of different types of steel on the market, and each supplier seems to have his own particular type varying just a fraction of a per cent. in the various parts that go to make up the steel. In view of this I would

like Mr. Johnson's remarks on the question of standardisation of steel and whether he thinks that the standard steels put forward by the British Standards Institution are any good at all in the question as to whether the standardisation of steel is, in practice, of any use whatever.

MR. JOHNSON : It is difficult for me to say when it pays to use high tensile steel ; it is really a question for the designer to answer. I may mention one case as an example, and that is the motor-bus. There have been restrictions there on the total weight of the bus and consequently the various manufacturers have got to cut down the weight in order to save weight so that they can carry more passengers and get more money on the journey. There it obviously pays to use high tensile steels wherever possible. There is also the question of reliability which comes in, and there are some steels which are definitely more reliable than others. It is rather difficult to express reliability in the form of tensile tests or any other tests, but if you are making a certain component and you do not wish to have any breakages in it (as if you did the reputation of the component would suffer), it then pays to use the higher tensile or more expensive steel. With regard to tubing—it is possible to get tubing in various tensile strengths. The air-hardening nickel-chromium steel is used for making axles for aircraft, and also there is a three per cent. nickel steel and a chromium-molybdenum steel which are used in aircraft. The chromium-molybdenum steel tube is used in America as it can be welded. With regard to the question of machinability. I rather imagine the difficulty due to threading is due to the method of manufacture in that certain surface defects are elongated and so interfere with the cutting. As to standardisation, I am altogether in favour of it. I think that it is essential to have it in order to keep the cost down to a reasonable amount. Consider the steel-maker, if he had to make steels to a specification that any individual firm might like to draw up—they would all draw up different ones—he would have to have enormous stocks, and consequently the cost would go up straight away. One of the arguments levelled against standardisation is that it tends to hinder development, but it is the policy of the British Standards Institution to revise their specifications in the view of recent progress and development. There are, of course, cases when something fails somewhere in a structure and you ask the steel-maker to supply you with a better steel. You find it gets you out of your trouble and then you have no time to see whether any other steel would cure the trouble ; you therefore decide to adopt that steel, and so another steel is brought into use. And so on. That may seem an argument in favour of non-standardisation, but the cases where special steels are required are not so numerous as one would imagine when one takes into account the thousands

of tons of steel that are used. Personally, I am altogether in favour of standardisation.

MR. FREESTONE: My remarks must be confined more to a commentary on the paper that has just been read. The ground that has been covered is very large indeed, and with most of the lecturer's remarks I have been in complete agreement. Most of the physical properties that have been shown to us this evening have been more or less obtained by myself in practice, but the question that occurs to me is this: when is this bewilderment going to stop? How many more steels are we going to introduce for the engineer to be troubled with? I picked up a steel-maker's catalogue the other day and I found that he had 54 combinations of chromium and nickel, and I looked round to see what our stores were like. I think if this document got into the hands of a draughtsman we should soon have 54 sorts of steel in our stores! I looked round, and although we had not reached the full quantity we were getting on that way. I thought it was time to try to find some line on which steels could be stored in readiness for instant use, especially in so far as it affects the business of a general engineer. A general engineer does not know from one day to another what material he may have to incorporate in the designs of his products. It seems to me from what I have heard this evening that it is just about time that the engineer put a break on the metallurgist and brought him down to earth a bit. By that I mean that the engineer should have a working knowledge of metallurgy and with that knowledge attempt to flatten out the trouble that he appeared to be getting into. To me it seems a very simple subject, as far as I can gather from the lecture this evening. Mr. Johnson has dealt with the basic carbon steel. He has told us the influence of carbon on steels, and he has left it at a point where, for ordinary commercial purposes, the carbon can stay at .55. I am not speaking of tool steels. He went on to the alloy group, and he selects two elements, chromium and nickel. Don't you think it is a question for the engineer to decide what influence carbon has on the steels and what influence nickel and chromium have on steels? It is simple to decide as far as the carbon group is concerned, but when we come to nickel-chromium we run off at a tangent. We find ourselves with a hard and soft steel; we find ourselves with a steel that when it is fully developed is capable of 100 tons a square inch, and yet we find on the other hand an austenitic steel that is perfectly soft and non-magnetic and capable of being hardened. Between these two extremes I think it is possible for the engineer to decide what he really wants. The difference in the physical characteristics of the material for the alloy group appears to me to be very small. A minute addition of chromium up to 0.15 appears to keep the material well within the range of a 65 ton steel, with a reasonable

izod somewhere about 30-40. If that is the case, and having realised what it means to add three or four per cent. of nickel, I think the time has come when engineers should begin to reject some of these fine graduations, fine additions of steel and chromium, and look for some standardisation whereby you can control your stores and incorporate into your machines the materials to use, based entirely on the physical characteristics.

Then the lecturer again left the alloy steels and got on to the low carbon steels. There again he got us into trouble. He touched on the case-hardening of steels. I would not have minded if he had kept to the question of the case-hardening of low carbon steels, but when he introduces chromium into a case-hardening steel, goodness knows what is going to become of us in a few years' time. However, the lecturer did not deal with those workshop problems that arise every day in connection with the carburizing of steel. He did not lead us on the path so that we can avoid the super-satuation of the case: he did not seem to realise that general engineers are not sufficiently financially strong in these days to employ metallurgists, and I should like him to tell us some simple formula whereby we could control this mass of material without having to resort to metallurgists. Finally, I would like to say that in the austenitic group of steels the engineer should realise that he has the choice of one or two things. He has a steel that is going to get him into a lot of trouble, or he has another one that might keep him out of trouble without resorting to the metallurgist, and as soon as an engineer starts handling an austenitic group of steels he is faced with the problem of restoring the material to its original austenitic state. The fact of turning a piece of austenitic steel or the working of it immediately upsets its characteristic, and unless it is fully recognised in the workshop we shall find ourselves sending out stuff that in a few years' time will be suffering from inter-crystallisation, and in that connection I would mention that in 1912 I had a very long discussion with Professor Brearley. That was in the very early days of stainless steel, and we had come up against what we thought was a trouble due to the rough handling of the material, the rough cutting of it, and as the subject was not very well understood in those days it was put down to the fact that the steel had been turned at too high a rate, but now we understand it to be inter-crystalline corrosion; but we found something more than that; we found that this inter-crystalline corrosion was not altogether due to the physical condition of the steel so much as it was due to its contact with a lead substance, and the fact of that being in contact with the lead brought about this inter-crystalline corrosion which has been referred to. The growth of these steels, the enormous number of them, must certainly give the engineer a good deal of food for thought, and the way I have tackled this

problem is to divide the carbon steels up in their groups—the chromium and nickel combinations into their group, and the austenitic steels we have left very much to themselves. I think it is necessary for the engineer to eject a good many of these fine implement values of chromium nickels and get down to British Engineering Standard Specification.

I would like to mention the screwing of tubes. We have had tremendous experience in this direction, both in carbon tubes and in the austenitic tubes, and with regard to the carbon group we have found that if you develop the physical characteristics somewhere in the middle order, that is to say, if you harden it and temper it for a reasonable period, we have never had any trouble such as tearing of threads or bad finish when that treatment has been given, and on the austenitic group of steels we have had considerable trouble with screwing, and the best solution we have found is a two per cent. solution of stannic acid in castor oil, and that got over most of our trouble as far as the screwing of austenitic steels was concerned.

MR. JOHNSON : Actually several of the steels shown on the slides were taken from various British Standard Specifications—anyhow the ordinary structural steels, the nickel, nickel-chromium and nickel-chromium-molybdenum, and so forth certainly are. The point where you mention there was 0.15 of chromium—the specification for a three per cent. nickel steel would allow up to 0.3 per cent. of chromium. That is probably to enable the steel-maker to use a certain amount of steel scrap, and chromium may get in that way ; but the main thing is to work from the point of view, as you say, of mechanical properties rather than of strict chemical composition, and provided you give the steel-maker a certain amount of latitude in the chemical composition which he must have, the main thing is to insist on his giving you the physical properties you want, so that whether it is 0·15 per cent. of chromium or not I do not think matters as long as it is, of course, to a definite British Standards Specification.

In connection with the selection of steels for general engineering ; there again it is rather difficult to make any definite recommendations, but if you have a heat treatment plant it is possible to use possibly one carbon steel and obtain quite a lot of properties by varying the heat treatment, and if you want a higher tensile material then you use a three per cent. nickel steel and get a variation in properties by varying the heat treatment, but then probably it will be necessary to employ a metallurgist. It is a question of deciding which is it cheaper to do, to employ a metallurgist and have one or two steels or to do without a metallurgist and have lots of steels.

I was interested in the remarks about cutting threads on the austenitic type of steel. They are not too easy to machine, although it is certainly easier to cut threads when they are in the cold worked condition. In connection with the ordinary steel tubes I take it that the hardening and tempering will alter the original cold-drawn structure of the steel and probably considerably improve it from that point of view.

With regard to inter-crystalline corrosion, I do not think that there is any danger of cold work producing this in stainless steels, nor did the original steel as invented by Brearley suffer actual penetration of the crystal boundaries.

In case-hardening the question was raised of curing expoliation and supersatuation. I think one of the causes of expoliation is due to the fact that the carburizing temperature is not kept absolutely steady. If it is allowed to vary up and down all the time you will definitely get trouble, and that is why people now are tending to put in automatic temperature control. It really does pay to go to the expense of fitting it. If you have not got it it is possible for furnace temperature to go up considerably which by producing free cementite naturally enables grinding cracks to be developed very easily.

Mr. Brooks : I should like to make an inquiry about a point in connection with stainless steel. There are two stainless steels, and I should like to know which is the easier of the two to machine. A rather peculiar point cropped up. We were making parts out of S.62 but we got better results out of S.80. The point is that S.80 is a little more expensive but cheaper to machine. It is a question as to whether the same part is not cheaper in the long run out of the more expensive steel.

Mr. Johnson : Actually I had a similar experience some years ago. We were using S.61 which is a similar steel, and it was in connection with some small gears, and very considerable trouble was experienced in machining. On changing over to S.80, which is an 18 per cent. chromium and two per cent. nickel stainless steel an enormous improvement was found in cutting and it was much cheaper in the end to buy the more expensive material than to buy the cheaper. The S.80 is also a better steel from the corrosion point of view.

Mr. Dudding : I have been very interested in the lecture and I think Mr. Johnson ought to be congratulated on putting in front of you such a wealth of data in a very easy form and in such a way that is was bound to raise a discussion. There are one or two points that strike me as an outsider. I have met a number of cases where these heat-resisting steels at high temperatures come into use, and it was not mentioned by the lecturer but it seems nearly always that what is more important is the intermittency of the heating and then the

actual resistance to oxidisation does not always determine which is the better thing. It is not only true of steels but it is true in other cases where you have any form of oxidisation or chemical reaction. Coming to this little controversy between the specification and the metallurgist on the one hand and the engineer on the other, reminds me of other meetings where a refractory maker and the glassmaker got together. All bad glass is due to bad refractories on one hand and on the other hand there never were any good refractories or any good glass. It seems to me, looking at these things again from an outsider's point of view, it is obvious that standardization is good. On the other hand you must have freedom of development or progress would come to a standstill.

Mr. Johnson : I was interested in Mr. Dudding's remarks, and in connection with the intermittency of heating I do not know whether that does apply so very much in the case of heat resistance steels. The only application where I can conceive it is in connection with aero-engine valves, or valves in high efficiency petrol engines. With regard to "creep" this can be explained by taking one of the heat-resisting steels shown. The quick test tensile strength at 800° C. is about 17 tons, but if you applied a stress of say five tons for very many days it would eventually break, and that particular steel would only endure a stress of about two or three tons per square inch indefinitely, which latter value is the limiting creep stress. In the case of valves which are continually being heated and cooled, I do not think creep stress definitely applies, as work which has been carried out at the N.P.L. shows that the fatigue strength of a steel tested under conditions of high temperature is very much greater than that of the creep strength.

Mr. Mollart : I have one or two practical questions to ask. With reference to water-hardened cast steel. We manufactured 100 bushes. We hardened those bushes ; quenched in water. They all appeared to be quite all right. After a period of twenty-four hours had elapsed possibly twelve of the hundred cracked. Twenty-four hours afterwards the next six went, and this went on until we had about half the bushes cracked over a period of five days. Can you enlighten me as to why that should happen and why the bushes cracked at different intervals ?

Mr. Johnson : I would say that one possible reason is the fact that the tempering operation is not done sufficiently soon after the hardening operation, but I understand that it is done immediately. There are two further stock reasons. The first is to blame the steel-maker and the second is to blame the hardener. If the steel is not suitable for the job it would crack, and if it is not properly soaked and you therefore have not an even temperature all the way through the bush it will crack, due to differential expansion. There is probably also slight variation in the steel from bar to bar and slight

variation in the quenching. You cannot say that every one is quenched absolutely identically, as they are presumably quenched in a batch.

MR. ROGERS: The speaker mentioned a weld decay in nickel chromium rods. A few years back I became acquainted with these rods and they suddenly developed flaws and broke. This was due to welding. The trouble was cured by not doing any more welding.

MR. JOHNSON: I think you are under a misapprehension with regard to the term weld decay. The steels I referred to were actually the high nickel chromium austenitic corrosion resisting steels. In welding ordinary nickel chromium steel difficulty is bound to be experienced because of the hardening effect. The steel is heated through the change-point and you get volume changes, and on cooling differential expansion is set up which produces minute cracks. That is a different thing altogether from the austenitic steels which are subject to weld decay. The weld decay in that case is, as I pointed out, cured by the addition of tungsten, titanium or silicon, and also by a suitable manipulation of the composition. It is not advisable to weld the ordinary nickel chromium steels but it is perfectly satisfactory to weld a modern austenitic high nickel chromium stainless steel provided it has got tungsten or titanium in it or it is possible to heat treat afterwards.

MR. FIELDS: With reference to nickel chromium steel bought in a hard and tempered condition, it is rather difficult to machine, so after normalising it we machine it quite satisfactorily, and re-harden and temper it. Is there any reason why we should not proceed under those conditions?

MR. JOHNSON: No, it is often done. It does not upset the structure of the steel at all. It is better of course to buy in the normalised condition. It is not advisable to heat treat it too many times.

MR. WEATHERLEY: It is a very great pleasure to propose a vote of thanks to our lecturer to-night, in as much as Mr. Johnson is a member of our Institution. It is fitting that such a subject, related as it is so to our everyday problems, should be dealt with by a member, and I am certain that all of you will agree that it is a fitting paper to record in our Journal. Mr. Johnson, we have enjoyed your lecture very much, and we thank you for the time and trouble you have given to it for our benefit and instruction. As you know, it is difficult for us to absorb all that you have put before us, but I am sure that all of us will study your paper when it is published. I hope the discussion which you have stimulated has been satisfactory to you.

The vote of thanks was cordially adopted.

MODERN LAPPING AND GRINDING PROCESSES.

Paper presented to the Institution, Glasgow Section, by the late Hy. Mantell, A.M.I.Mech.E., M.I.P.E., and to the Eastern Counties Section, Ipswich, by W. Ogilvie.

Progress.

CONSIDERATION of the modern invites comparison with that which has gone before, because, by comparison, the extent of progress can be measured and the reason of current practice determined.

Progress can, in this instance, be measured by reviewing advancement over a very small period of time. R. E. W. Harrison, in an article published in *Machinery* (actually based on a paper presented before the American Society of Mechanical Engineers), states that to achieve an accuracy of 0.0005 inch by grinding, the unit cost has decreased as follows :—

1924	... ...	Unit cost 4
1929	... ...	,, ,, 1.6
1932	... ...	,, ,, 1

whilst to obtain an accuracy of 0.0002 inch, unit cost has decreased at the following rate :

1924	... ...	Unit cost 6
1929	... ...	,, ,, 4
1932	... ...	,, ,, 2

A number of interesting thoughts are provoked by these statements ; the most important being that costs mount terrifically as one aspires to the last " quarter-thou."—and in fact it is relatively more expensive to go from 0.0005 inch to 0.0002 inch in 1932 than it was in 1924 although, in actuality, to work to the finer tolerance in 1932 only costs half of the sum involved in keeping within the coarser tolerance in 1924.

So much for progress ; the reason lies in the insatiable demand for cheaper and better comforts which the world demands. And—for this one is profoundly thankful—the production engineer does not cheapen a thing by reducing quality ; the history of this mechanised age shews that every time a commodity is brought within the reach of a greater number of people its efficiency has been increased.

Glasgow, 15th December, 1932. Ipswich, 4th April, 1933.

Definitions.

Before proceeding further, it is thought advisable to define certain terms which refer to the processes of grinding and/or lapping.

Grinding.

A general term used to denote the cutting of any material by means of small particles of a substance harder than the material. Grinding is usually "line contact" or "limited area contact," and the paths of the cuts are usually parallel.

Lapping.

A process of removing minute portions of material by means of a cutting agent similar to that used in grinding but much smaller in size. Lapping is usually "line contact" or "broad area contact" and the paths of the cuts are usually criss-crossed because of the combination of reciprocating and rotating motions or of two rotating motions in parallel planes but eccentric one with the other.

Honing.

A process mid-way between grinding and lapping. The coarser cutting agent of the former is caused to take up the criss-crossed paths of the latter.

Polishing.

The removal of still finer portions of a material by using still finer sizes of the cutting agent or—a most important "or"—by bending minute particles of the material being polished from a vertical or radial position into a horizontal or arc-like position. In the latter case, a substance softer than the material is used and the required deformation is caused by pressure combined with frictional heat. Each of the four methods can be sub-divided; for instance, there is a wide gap between snagging a steel bloom and grinding the pins on the crankshaft which is made from the bloom, yet each process comes under the heading of grinding. For the purpose of this paper we will only consider grinding as a process in which the cutting agent and the work piece are each moved or in which one is secured by some mechanism but in either case a precise relationship is maintained between the two.

Of the four methods mentioned above, the first three are of varying degrees of precision; the last is merely used to obtain "finish" and this by methods which often destroy accuracy.

Until recent years, the grinding process was only used as the final means of obtaining precision; it is one of the purposes of this paper to show that the biggest change in the use of grinding and lapping is that these processes are not now primarily the means of correcting imperfect work but are definite metal removing agencies of varying degrees of precision.

Early Uses.

The old conception of the use of grinding machines is preserved in the name given them by the French, i.e., " machine à rectifier " ; this, a survival from the days when other machining operations could not produce work to size and truly round or flat, as the job demanded, and within the elusive thousandth. This disability was largely occasioned by an imperfect knowledge of metallurgy for, although machines and mechanics—and especially mechanics—were capable of producing work to the accuracy demanded by designers of 35 to 40 years ago, the process of hardening or heat-treatment so distorted the work that some method of re-claiming it became necessary. The increasing ability to measure to within one thousandth of an inch brought in its train a widening apprecia-tion of the possibilities of interchangeable manufacture and, whilst the skill of the old-time mechanic could conform to the requirements of this development, it was at the cost of expense in time and plant. Even so, the mechanics' skill was only applicable to unhardened materials.

In its earlier stage of development, grinding was only used to rectify work pieces distorted during hardening. The early machines used for this purpose were extremely light in construction and in design were the forerunners of present-day universal grinding machines. The wheels were seldom more than eight inches diameter and the amount of work they were expected to perform can be esti-mated from the width of the driving belt which was usually about one inch.

Needless to say, time was not the essence of the contract—providing the machine did that which was not possible by any other means, i.e., machined hardened parts, it was considered to have done all that could be required.

Following this stage, a few pioneers pursued the thought that if turning could be carried to the " roughed-out " stage and the work completed by grinding—whether the work was hardened or otherwise—the total time would be less and the result *at least as good*, if not better.

As opposition became converted so grinding developed and became more specialised. First, the plain grinder which, as its name implies, only deals with plain cylindrical work. Then crank grinders, cam grinders, roll grinders and other machines, each going through the stage in which the machine was almost hidden by a forest of belts ; from there to the " mechanical self-contained " machine, on to modern hydraulics.

Wheels.

Concurrent with the advance in grinding machine design, and the severity of the requirements in ever-increasing accuracy and finish,

has been the progress in abrasive wheel manufacture. Starting with vitrified wheels of natural emery, engineering has now at its disposal wheels of artificial abrasive described as being of controlled structure and in a choice of bondings to suit a wide variety of purposes. The modern wheel is responsible for the success of modern machines for, without an approximate guarantee of consistent performance of the wheel the excellent features of modern grinding machines would be of little use.

Apart from wheel structure, the most noticeable—and certainly the greatest money-saving advance in wheel design has been the increase in the diameter of grinding wheels. Prior to 1922 or 1923, the standard diameter wheel for a six-inch plain grinder was 14-inch ; at that date a manufacturer introduced a machine carrying a 24-inch diameter wheel and, a little later, introduced a 30-inch diameter wheel in place of the standard 18-inch diameter wheel on a 10-inch machine.

The advantages of this change are manifold, some of them being yet imperfectly recognised. In the first instance, the increased strength of grinding wheel bonding which permits of surface speeds up to 6,500 feet per minute could be exploited without increasing the revolutions per minute of the spindle. To take a 10-inch machine as an example and estimating on a maximum surface speed of 6,000 surface feet per minute (which is the maximum recognised by several of H.M.'s Inspectors of Factories) we find that the new wheel of 30-inch requires a spindle speed of 764 r.p.m. as against 1,273 r.p.m. for an 18-inch wheel. Even when the larger wheel has worn down to 24-inch diameter, only 955 r.p.m. is required against the 1,637 r.p.m. for the 18-inch diameter wheel when worn an equivalent amount. This has had a profound effect on spindle and bearing design.

Another advantage lies in the fact that any increase in wheel diameter obviously increases the surface length of the wheel, therefore at the slower revolutions required to give the same surface speed to the larger wheel it will be seen that each individual grain of abrasive will come into contact with the work less frequently in a given time. This gives an increase in the length of time between " wheel dressings," or, expressed in another way, an increase in production per dressing. To appreciate the worth of this advantage it is necessary to observe the amount of material removed per dressing of the wheel. Reflection will point to the fact that it must be at least three times as much as is used in actual work for it is clear that when a facet of an abrasive grain becomes dull, not more than a quarter of it has been used, leaving three-quarters to be torn away from the bonding before a set of fresh grains are exposed. The finer the finish required on the work piece, the more is this " waste " of abrasive aggravated, therefore the introduction of the larger wheel has brought a big increase in the useful life of the abrasive with a consequent decrease in the " cost of wheel per piece produced."

Hydraulics.

For many years, much thought has been given to the subject of hydraulics by machine tool designers. Some considerations of this question have been placed before the Institution of Production Engineers, sufficient for us to record an opinion that grinding presents the easiest application in that the operation usually consists of a series of light cuts continuously applied which prevents the jumping action which is sometimes noticeable in other applications. The advantages of hydraulics applied to grinding machines can be summed up as the elimination of trains of gears and in the ability to provide a cushioning effect at the reversal of the table in a very simple manner, thereby allowing table traverse to be increased so that it is now possible to set table speeds as high as 40 feet per minute against the nine feet per minute possible on mechanical traverse machines. It is true that it is not possible to take full advantage of the maximum traverse now available but as experience widens, this factor will be used to increase production.

The use of hydraulics is not confined to table traverse. One particularly serviceable application being to the rapid in-feed and out-feed of the wheel head on crank grinding machines also, to the rapid withdrawal and advancement of the work steady on the same type of machine, and a further application embraces the work clamps. Incidentally, this latter feature is usually interlocked with the work head motor so that rotation of the crank is not possible unless it is securely clamped.

Electric Drive.

Mention of a work head motor brings to notice the increasing use of direct motor drive. In the early stages of this development, one motor replaced the main driving pulley and all other motions were obtained as before. Now it is not uncommon to find machines with two, three or four motors, each machine function having its own drive, that applied to the work head being, as a rule, a D.C. variable speed motor and, in those places where D.C. is not available, a generator of sufficient capacity is driven off one of the subsidiary drives, e.g., the water pump or the hydraulic oil pump. These are the principal constructional developments which have evolved from the basic design.

Centreless Grinding.

An even more interesting evolution from crude simplicity to modern productivity is to be found in the centreless grinder, for in little more than a decade the machine as known to-day has grown from a very unimpressive beginning until in 1932 it is seriously challenging the centre type of grinder on every job of reasonable diameter.

My own company have been interested in the centreless method of

grinding long before its general introduction to the market. The obvious advantages were attractive to progressive production engineers. For instance, the saving of time due to the elimination of inserting the work between centres, provided an opportunity to lessen costs. Another saving was to be found in the much heavier cuts possible by the full support to the work instead of supporting it on centres and steadying it by hand-operated steadies demanding delicate adjustment for each work piece. The machine as manufactured was that designed by H. A. Dudgeon, and used for the manufacture of chain rollers and pins. Although the machine in question had a very limited application and has now been superseded by a basically different design, there is no doubt that the invention of Dudgeon's did much to put the operation of centreless grinding on an acceptable basis in the English market.

Application of Centreless Grinding.

Early models of centreless grinders were designed to deal with straight parallel work of truly round cross section in relatively short lengths, but the field of usefulness has been so extended that there are very few grinding operations which now come amiss to modern centreless grinders. A comparatively early achievement was to grind equi-distant notches at six-inch intervals in bars three feet in length; the requirements of the job being accuracy in the width of the notches and concentricity between the original diameter of the bar and the reduced diameter of the notch; the component in question being a textile machine part. Fountain pen barrels provided an interesting job, partly because of the material being unusual and partly because of the two tapers. After this, the problem of grinding glass rods proved easy of solution. Numerous "out-of-balance" components are being ground on centreless machines, one example which comes to mind most readily being motor car stub axles. Not only is the part out of balance but great accuracy of both size and concentricity must be obtained on the ball race fits. Form grinding is now a commonplace; projectile and automobile pistons provide two excellent examples. In one case the accuracy of the rounded nose is important, in the other the concentricity of the different diameters of the piston ring lands must be considered.

Fundamentals of Centreless Design.

Three fundamentals form the basis of centreless grinder design. These will be enumerated briefly and a more extensive description follows:

(1) The elements of the machine consist of a grinding wheel running at high speed, a control wheel for revolving the work, running at a slower speed and a support for the work.

(2) When the work is passed straight through the machine, the means adopted of achieving the necessary motion is to

incline the axis of the control wheel or the centre line of the work rest slightly out of parallel to the centre line of the two other elements.

(3) Whatever device is employed to true the two wheels must be such that the faces of both are parallel to the axis of the work at the point of contact.

The possible variations in the arrangement of the above-mentioned three fundamentals are many. The reasons for the selection of those which are incorporated in B.S.A. design will now be described ; this make is taken as an example because it is the one with which the author has the greatest experience.

The first consideration concerns which of the wheels must be moved in relation to the other in order to accommodate work of different size or to apply the cut. In the B.S.A. machine, the control wheel is the fixed member and the grinding wheel is adjustably mounted on flat and vee slides of large dimensions. For " straight-through " work, the grinding wheel head may be locked in any one position after being adjusted to give the required dimensions to the work piece.

The advantages of moving the grinding wheel member are manifold. In the first place it is the heavier of the two wheel heads and therefore less likely to react to any tendency to set up vibration. In the second place, which is one that has a marked effect upon the amount of work produced over a working week, is the fact that, as the grinding wheel requires dressing far more frequently than the control wheel, the fixed position of the control wheel and the work rest on the B.S.A. machine does not necessitate resetting after every grinding wheel redressing, but only upon those much rarer occasions when the control wheel has to be re-dressed. Yet another reason is to be found in the term " control wheel " for the word " control " is no empty phrase. This demonstrates the need for the utmost rigidity to ensure that the control wheel really controls the work piece without the slightest vestige of chatter.

Other features which go to support the above advantages are to be found in the following details. The work plate is carried on a support which is mounted on the base of the machine and so arranged that the plate can be moved to or from the control wheel when setting up to accommodate different diameters of work, or as mentioned above, to readjust the setting after the control wheel has been dressed. This construction, embodying a fixed control wheel head, is of marked advantage when using the machine as a bar grinder or for any other purpose which necessitates outboard supports. Obviously, the more of these supports there are the greater the advantage shown, for to adjust a series of work rests in order to re-align them at each dressing of the grinding wheel would

necessitate a long and tedious operation.

A further refinement in connection with work plates on the larger machines is the method of raising or lowering these plates in order to bring the work to the correct centre height in relation to the wheels. This is performed by means of cams on the larger machines.

Yet another refinement is to be found in the position of the side plates used for guiding the work into and out of the machine. These are high up on the wheel guards therefore the slides upon which they are mounted and along which they are adjusted are away from all the grinding sludge.

It is always interesting to study methods of securing accuracy when applying the cut. This is achieved by means of a very accurate lead screw, operated by a rotating nut which in turn is actuated by means of a micrometer hand wheel. This is more or less common construction but the particular feature applying to the B.S.A. design is the provision of widely spaced divisions (one division = $\frac{1}{4}$ inch), each one of which represents a movement on the grinding wheel head of 0.0001 inch.

Method of Drive.

Mention must be made of the method of drive. In designing this feature, the primary consideration is undoubtedly to get as much power to the wheel spindle as is possible, so that the maximum of work can be performed without any risk of stalling the wheel, with the consequent detrimental effects upon the machine and the work. The second consideration is to arrange the drive so that in the event of a breakdown in this feature, a change can be made without disturbing the setting of the spindle in its bearings. Obviously, any form of truly endless belt is useless in regard to the second consideration. In dealing with the first, experiments ranging over a very lengthy period have been carried out, and for some time past, a perfected roller chain drive has been fitted. This provides a definite drive yet in no way detracts from the quality of the work.

In order to progress work through the machine, the control wheel head is so designed that the spindle is carried in a heavy angle bracket which can be swivelled through 7° from the horizontal by means of a suitable adjustment provided between the spindle carrier and the main casting. The rate at which the work is fed through the machine depends upon the speed of the control wheel and its angle of inclination. For instance, when the wheel has a peripheral speed of 50 f.p.m., and is inclined at an angle of 1°, the rate of traverse of the work piece through the machine is 0.87 f.p.m., whilst with a peripheral speed of 150 f.p.m. and an angle of inclination of 7°, the work passes through the machine at a rate of 18.30 f.p.m.

Wheel Truing.

Consideration can now be given to the question of truing the grinding and control wheels. Even in the earliest grinding machines of the centre type it was found necessary to place the diamond in such a position that the wheel dressing operation was performed in full view of the operator, for only by making full use of the two senses of sight and touch could a high degree of finish and accuracy be obtained. Obviously, this co-ordination of the senses becomes of greater importance as the demands upon grinding machines become more intense. A further reason demanding the diamond in full sight of the operator is the economic necessity for keeping wheel costs at a minimum. If, during the life of a wheel, the operator causes the diamond to " dig in " through blind working, then too much of the wheel is being consumed for no useful purpose. These, then, are a few primary reasons for mounting the wheel dressing diamond on centreless grinders where it is in full view of the operator. The lightest touch, verified by sight, is sufficient to bring the wheel to that state of perfection which will produce work of excellent finish and true to the finest working tolerance. On these machines, the wheel dressing unit is carried on a compound slide mounted above the wheels and on the fixed member of the machine, so that its path is always parallel to the axis of the grinding wheel spindle. This construction, which must be carefully noted, employs only one compound slide, thereby overcoming the very real constructional difficulty (and, probably of greater importance, the problem of maintaining accuracy throughout the life of the machine) of securing alignment of two compound slides. This alternative construction is adopted almost universally, in fact, the author cannot recall any other centreless grinder using one slide and one diamond for truing both wheels in full view of the operator. The economy of having only one diamond in use (an important point when many machines are installed due to the reduction in idle capital tied up in such expensive articles as diamonds), is effected by having the diamond mounted in a holder which can be accurately rotated through 180°, therefore the same diamond is used for truing both the grinding and the control wheels. It will be clear that this construction gives an absolute guarantee that both wheels are trued to give a line of contact parallel to the grinding wheel spindle, irrespective of the angle at which the control wheel is set. A further advantage of this construction is that the grinding wheel may be trued at any point above the point of contact with the work, so that the diamond may be kept set in one position and so be ready for re-dressing without any delay. This applies to " straight-through " work, infeed work and to the grinding wheel only. Naturally, the control wheel must be dressed at the point of work contact, but as this is a much less frequent operation, vertical movement of the wheel dressing unit is

of infrequent occurrence. When using the machine for form grinding it is necessary to dress both wheels at the point of work contact, otherwise a true form will not be reproduced.

Internal Grinding.

Internal grinding suffers many limitations. If even 5,000 s.f.m. is taken as a reasonable speed for artificial abrasives then a wheel $1\frac{1}{2}$-inches diameter must run at nearly 13,000 r.p.m. which, coupled with the bad conditions under which an internal grinding spindle works, introduces a most unwelcome cause of inaccuracy. In grinding a hole which is relatively long compared with its diameter there is the additional handicap of the " hammering " of the wheel. Despite these inherent troubles, a few machine-tool makers can point to machines which do a good job. Improvements in spindle design make high speeds possible and this fact has been seized by the advocates of another method of "finishing" bores, i.e., by the use of the diamond or, in some cases, tungsten carbide tools. This process is not yet capable of universal adoption but it is one which is being watched with interest and developed with activity. Some extraordinary results are being obtained with a Continental machine designed for the final operation on automobile cylinder bores and the like. Its advent is likely to arrest the triumphal progress of the hoving process. These very sketchy comments on the internal grinding process will reveal the necessity for extreme caution on the part of production engineers when deciding upon the installation of plant for finishing holes.

Surface Grinding.

Another method of grinding which never fails to arouse a good debate is the surface method, especially when it encroaches upon the province of the milling field. Each advance made by one is countered very quickly by the other but, of course, where hardened parts are concerned, grinding is supreme. Probably the most used type of machine for dealing with hardened work pieces is the one originated by Blanchard. Where large numbers of similar parts are concerned the automatic type is an extremely fast producer but an objection sometimes raised against this particular type is the direction of the wheel marks.

External Honing and Lapping.

This brings us to a consideration of external lapping and honing which processes are used when the finish and/or accuracy obtained by surface grinding is open to criticism.

Let us first consider work pieces which have to have their two sides truly parallel. If such pieces are thin (such as, for instance, piston rings), there is the danger of distortion when holding them on a grinding machine, added to which is the fact that one side only can

be operated on at one time. It is an axiom that each additional sitting introduces a factor of inaccuracy. However, these pieces do not require the highly polished surfaces associated with lapping, in fact, such surfaces are stated by designers to be undesirable. Therefore, external honing is performed by substituting on a standard lapping machine, plates of abrasive of relative coarse grain for cast-iron plates charged with fine abrasive powder. By this method, the work is retained in a fixture which allows full " float," i.e., there is no distorting influence and, further, the upper plate of abrasive floats to permit of self-alignment with the lower plate.

To the naked eye, an externally honed finish is superlative ; in practice, the minute channels which are still there prove objectionable in that, when a component has to work under high pressure and packing is not desirable, seeping takes place. This, and some other applications, calls for surfaces which can be " wrung " together in a manner similar to that employed in building up slip gauges. To obtain this, the finest form of accurate finish, lapping is the process to employ. The same process is used to finish I.C. engine valve stems and piston pins in common with a large number of other parts which must be as nearly frictionless as possible.

General Conclusions.

(1) Modern grinding is, in some cases, able to compete with other machining processes as a metal removing or " roughing " operation.

(2) Despite the assertion just made, it usually will be found more economical to " break down " the work piece to within .020-inch to 0.12-inch of finished size by the use of another type of machine and use a grinding machine for the finishing stages.

(3) Because of the permissible tolerance mentioned in (2), prior operations need not be held to a high degree of accuracy as to size.

(4) Wherever possible—and the possibilities are increasing rapidly—centreless grinding should be used because it is quicker to manipulate in addition to being a quicker remover of metal.

(5) Internal honing is a better process than internal grinding when the bore to be finished is (*a*) more than twice the length of its own diameter or (*b*) is in a work piece which cannot be rotated.

(6) External honing is not a metal removing process, the maximum amount to be left for removal should seldom exceed .002-inch.

(7) Lapping is even less a metal removing process ; attempts to remove more than .0004-inch are not economical.

A Specific Conclusion.

The whole of the author's experience stresses the truth that no operation or method should be expected to correct an inaccuracy which has been allowed to occur at a prior operation. Each

machining operation in a sequence must produce work as true as possible to form; the function of succeeding operations being to advance another stage towards precision of size and/or finish. Within the author's knowledge there is no exception to this rule.

PRECISION GRINDING.

Paper presented to the Institution, Manchester Section, by R. Whibley, and also read at London and Sheffield Sections by H. Taylor.

BEFORE Members of your Institution it is not necessary to explain away the ambitious title of this paper. To give a complete outline of present-day grinding practice in an hour's talk is an impossibility but the following notes on present-day tendencies in grinding machine design and use may be of interest. For convenience in presentation the examples and illustrations are drawn almost entirely from the practice and experience of the company by whom the author is employed. The company has been building precision grinding machines for 26 years and the examples are representative of present-day practice.

Grinding Wheels.

Grinding practice and all that it means to-day in production was born of research work which a generation ago resulted in the making artificially in the electric furnace of silicide of carbon and fused aluminium oxide or alumina, on a commerical scale. The actual production of these artificial abrasives is to-day a comparatively simple matter but the turning of them to their most efficient use in the form of grinding wheels and segments is continuously in process of development.

The grinding machine is literally built round wheels composed of these artificial abrasives with their millions of cutting points each giving its quota of chips before it breaks away from the wheel bonding to expose a new cutting point. High claims are made for some of the new metal alloys but the grinding wheel of artificial abrasive with its cutting speed of 2,000 to 6,000 feet per minute, stands supreme.

The author believes the grinding machine maker has been continually held back by the grinding wheel maker and demands for improvement in grinding wheels are insistent. The grinding machine maker expects the grinding wheel maker to develop further the use of the wonderful abrasives available. The principal requirements are a more consistent grading and particularly a wider range of usefulness and efficiency in each of the different gradings. Some classes of work now call for very fine shadings of difference in wheels,

---

Manchester: 12th December, 1932. London: 6th January, 1933. Sheffield: 10th April, 1933.

and the many weeks which apparently are still necessary to make so called special wheels is an immense handicap to production.

The necessity for research in the direction of giving any one grading a much wider scope in dealing with slight differences in materials, is clearly indicated, while a grinding wheel maker who could meet any reasonable requirements in grit, grading, and wheel size in 24 hours would quickly have to extend his works. It is all too common to see costly machines standing idle and production held up for six weeks while some special grinding wheel is made and uncertainly kilned.

Finish.

From grinding wheels it is natural to pass to the question of finish. No aspect of grinding can be so misleading. The really ground finish always shows abrasive grit lines or chip furrows, and although time spent on finish grinding can give a very bright finish, such a finish always shows these furrows and is totally different from a polished or mirror finish. Immediately a grinding wheel starts to polish the surface it ceases to grind. As long as the grinding wheel is really grinding accuracy in the work can be maintained.

If a polished surface is necessary it is no function of the grinding machine to give this result. Polishing must be carried out by special means designed to remove no more material than that represented by the depth of the minute chip furrows which exist in a true ground surface. Such special polishing operations are very rarely used but a special instance is that of polishing rolls used in certain metal rolling operations such as in the production of tin foil which is rolled to the extraordinary thinness of ten-thousandths of an inch thick. Another example is the production of gold leaf. Such polishing operations occupy days and the processes are generally held secret by the firms employing them. Another example is the lapping of gudgeon pins and crankshaft pins. Although lapped the accuracy depends entirely on the grinding machine used prior to lapping.

Ordinary methods of polishing a ground surface serve only to destroy any accuracy the grinding operation may have produced. Even a lapping operation must be carried out with great care if the accuracy given by the grinding machine is to be maintained. On the question of finish let me instance a railway carriage axle journal which has been finish, turned and then rolled to give that highly burnished finish which has been considered essential. The method is still largely used. To check the roundness and parallelism, a light lapping with a cast iron lap was carried out. The variation from roundness amounted to six-thousandths of an inch while non-parallelism amounted to seven-thousandths of an inch. The journal

was much more accurate when it left the lathe than it was after the finishing operation of burnishing.

During the first stages of any grinding operation in which a good commercial finish is required, metal is removed as quickly as the machine, the grinding wheel, and the work, will allow, but as size is approached there is a progressive showing up in the rate of metal removal, and the higher the finish required the longer is the period occupied by this tapering off of metal removed. In this way the time occupied in obtaining a high finish is often many times longer than that taken in removing 95 per cent. of the metal. For example, when grinding the bores of aeroplane engine cylinders, ten or fifteen thousandths of an inch may be removed in ten minutes, whereas the building up of the necessary finish may occupy an hour or more.

Practically every grinding operation passes through these stages. After bringing up the wheel metal removal rapidly increases until the limit is reached. This limit depends on the work, the type of grinding, and the machine. Metal removed continues at this maximum rate until size is approached, but from this stage the speed of metal removal falls off at first rapidly and then progressively more slowly. For very high finish the curve dies out very gradually indeed.

Hydraulic applications.

Possibly no development of grinding machines has been watched more closely by production engineers than the application of hydraulic movements. The first hydraulic grinding machine seen in this country was imported by the Greenfield Company, of America, in 1916. The past five years has seen a continuous transition from gear traverse to hydraulic traverse and the subject is one to which all grinding machine makers are giving their attention.

Take an oil circuit for hydraulic traverse of a grinding machine table. A gear pump feeds oil at a pressure of 80 to 100 lbs. per square inch to the control valve which usually is the reverse valve connecting directly to each end of the ram cylinder. The cylinder is double acting and by means of the reverse valve each end is alternately supplied by oil at pressure, and on the return stroke the oil passes freely through the reverse valve to the oil sump from which it is again pumped. If the speed of the table is reduced by throttling a relief valve bye-passes the excess oil direct to the sump. The system could hardly be simpler, the satisfactory working out of all the details has proved another matter, and good as some present-day examples of hydraulic movements are, there is still plenty of scope for research and experiment.

Hydraulic traverse is capable of giving traverse speeds that are impossible with gearing while the ease with which any desired

speed can be obtained is an outstanding advantage as compared with the clumsy method of steps through a gear box. The fitting of hydraulic traverse has with some classes of grinding machine trebled production. This great increase of productive power is available in all cases where the speed of the work past the grinding wheel is given directly by work table speed. On vertical spindle surface grinders, table speeds of 65 feet per minute are now available as compared with 18 feet per minute obtainable by gear traverse.

A method of applying hydraulic traverse to a vertical spindle surface grinder table may be referred to. The cylinder, which is of the double-acting type, has a stroke only one-half that of the table, the increase in speed in the ratio of 2 : 1 being given by sprockets on the crosshead carrying two chains, one end of each of which is anchored to the machine body while the free ends pull the table at twice the speed of the hydraulic piston. This arrangement gives a most flexible movement to a long and heavy table and obviates the use of a full length cylinder with its consequent increase in floor space.

On surface grinders with periphery wheels, and on spline grinding machines, the same increases in output are possible by the use of hydraulic traverse. A high speed of traverse and an accurate control of this speed are also of great advantage in all internal grinding operations. On crankshaft grinding machines hydraulic traverse movement shows to great advantage in the speed with which the grinding wheel can be withdrawn from between the crank webs before the work table is moved to bring another crankpin or journal opposite the grinding wheel which can then again be brought to the grinding position by the hydraulic return movement.

On many plain grinding operations quick hydraulic withdrawal and return of the wheelhead provides a great measure of safety to the operator who otherwise would risk his hand in insertion or removal of work rather than laboriously withdraw and return the wheel by hand. This danger is a very real one. The projection of the worm wheel between the two grinding wheels makes a quick withdrawal and return of the wheelhead essential for safety and speed in operation. Previously this operation was carried out by a single wheel the work being turned end for end when the second diameter was ground. The production was 30 per hour. Hydraulic withdrawal to the wheelhead was applied, operated by the same lever that stopped the work rotation and turned off the water, and these changes combined with the use of two wheels brought production up to 120 per hour, that is, a quadrupling of output. The saving is almost entirely due to simplification and reduction of handling.

The author's company has, during the past few years, fitted many types of grinding machine with hydraulic traverse or other hydraulic movements, and such movements are standardised on the various

classes of machine mentioned above. The advantages of hydraulic traverse on plain grinding machines are, however, not so apparent. Maximum work speed past the wheel has always been easily obtained by the simple expedient of rotating the work to give a surface speed about 60 feet per minute, past the head. Table traverse on a plain grinder is equivalent to cross feed on a surface grinder and high speeds of table traverse cannot be used. A gear traverse gives all the speed of traverse necessary. Hence, production on a plain grinder with hydraulic traverse is not necessarily faster than on a gear traverse machine, and the purchaser of a high-priced plain grinder will not obtain a production commensurate with his heavy expenditure simply because such a machine has hydraulic traverse. In America, and to a less extent in Germany, a considerable development has taken place in elaborate and exceptionally heavy, small and medium capacity plain grinders. During comparatively prosperous times such expensive machines have found a market despite the fact that machines of gear-driven type would give equal production at much less machine cost. The user has already learned to expect that hydraulic motions and high cost go together, and it has been too hastily believed that hydraulic movements mean necessarily a better plain grinding machine with increased production proportionate to the price of the machine.

There is, however, a useful if limited field for these heavy and costly types of plain grinders but these uses do not represent more than two or three per cent. of present-day plain grinding operations. A British machine of this type weighs $5\frac{1}{2}$ tons, although of a capacity of only 10 inch by 36 inch. Hydraulic table traverse and hydraulic wheelhead quick withdrawal and return are fitted, while the wheelhead feed is also applied hydraulically. The gear box gives the changes of speed for the workhead. A single lever stops the work, stops the table traverse, withdraws the wheelhead, turns off the water. A return of the same lever after a new piece has been inserted stops the work and table, brings the wheelhead up quickly, and turns on the water. Such a machine costs roughly twice as much as a gear-driven machine of the same capacity, but the gear-driven machine has probably an equal productive capacity. Unless the elaborate hydraulic machine is used only in those few cases where its particular advantages of massiveness can be exploited, its installation is very seriously uneconomical as the expenditure cannot be justified.

Hydraulic traverse on plain grinding machines gives a gratifying convenience in handling and speed control, and a much better-looking machine can be produced than is possible with gear traverse. Such advantages have a value, and there is no doubt that hydraulic traverse in small and medium plain grinders has come to stay, but to be worth buying the cost be comparable with that of present-day

gear-driven machines, and this can only be achieved by simplification which after all is the surest evidence of development.

The author's company has lately carried out a very great deal of experimental work in this direction and I may mention a plain grinding machine which it is thought will prove a definite step forward in plain grinding machine design. The table traverse is hydraulic but all components of the hydraulic equipment have been subjected to a simplifying process—the general tendency has been up to now, the multiplication and elaboration of hydraulic equipment. Diagrams of the hydraulic systems of some machine tools must surely by their complexity assure the user that he is obtaining value for money. Simplification has resulted in a much freer flow of oil through the control valves and their connected piping. When the hydraulic table traverse is stopped the hand traverse is automatically engaged and here is a very important point, the hand traverse is very light and sensitive. No doubt many have experienced the annoyance of heavy hand traverse on hydraulic traverse machines.

The workhead has its own individual motor. From the size of the motor—only some six inches in diameter for $\frac{1}{2}$ h.p.—it might be supposed that this small power unit was imported; it is, however, very encouraging for the machine tool maker that such motors are now obtainable in this country. Despite its small size this motor is of the variable speed D.C. type, the variation of speed being given through a combination of control gear and generator, the generator being driven from the main backshaft of the machine. The range of speed available is such that the highest and lowest speeds have a ratio of at least 6 : 1. The total range is covered without the use of pulleys or other loose parts.

It should be mentioned that the motor axis is across the machine so that any residual vibration is along the work axis—a direction which does not affect finish. Drive from the motor is by V-belts to a worm and worm wheel to the work driver. The worm and its shaft are in nitralloy steel, the worm being assembled direct from the nitration hardening without any finishing or grinding process. In this way the accuracy of form given by the worm generating machine is maintained since no distortion whatever is induced by the nitration process. The drive to the work gives as smooth a drive to the work as is obtainable on a simple work spindle driven direct by long belt from an overhead countershaft. The entire absence of spur or helical gears or chain obviates chatter in the work finish.

The wheelhead is in the form of a box which braces rigidly the two-wheel spindle bearings. The box also encloses the multiple V-belt drive to the wheel spindle although any necessary adjustment is effected easily from the rear.

The sliding ways are pump-lubricated with filtered oil, and the variable automatic cross feed has trip and dead stop in fixed relationship, the movement of trip on which size depends being independent of speed of table traverse or the amount of feed. The machine is self-contained for drive by a single constant speed motor.

Wheel spindles and bearings.

The grinding wheel spindle and bearings are without doubt the most important assembly in any grinding machine. Until two or three years ago chrome nickel steel grinding wheel spindles were used very widely and by most grinding machine makers. Unfortunately, there always appeared an element of doubt as to the uniformity of the finished spindle surface as between one spindle and another. With apparently identical steel and identical treatment, a small percentage of these spindles would show tiny surface cracks, after running for a time. The steel, even with the most careful heat treatment, had not the stability in its structure or all-through absence of stress to avoid slight distortion with time, heating up, or slightly adverse conditions during grinding. These spindles generally ran in bearings which comprised a hole or bore leaving a definite annular clearance for the oil lubricating the spindle. Because of the instability of the steel this clearance had for safety to be grater than was necessary from consideration of lubrication only. These spindles were, however, the best that could be obtained until recently.

The author's company was the first to use chrome nickel steel for grinding wheel spindles and they have been the first to use the new nitralloy steels for this purpose. Nitralloy steel spindles have resulted in a remarkable all-round progress in grinding ; grinding finish is improved ; the risk of chatter so far as it arose from the spindle, has been eliminated, and indirectly the use of nitralloy steel has caused a reconsideration of grinding wheel gradings that had for any one class of work become firmly established for use with the chrome nickel steel spindle.

About the time experiments were being carried out on nitralloy steel spindles one type of grinding wheel spindle bearing, I may say, was developed. A feature is that the lower half of the bronze is firmly secured to the main casting by heavy cheese head screws while the upper half is not secured to the casting in anyway but is quite free to seat itself on the spindle so that in effect the lower half bronze locates the spindle definitely in position in the main casting while the spindle in turn locates the upper bronze. It will be clear that the lower half bronze is of the greater importance since it governs all running steadiness of the grinding wheel and the strictly accurate relation of the grinding wheel to the work. To give even more definite location to the spindle a groove (about

$\frac{3}{4}$ inch wide, in a four inch spindle) is cut away so that the spindle cannot seat at this point at the bottom of the bearing but is in effect supported by two arc surfaces and is kept in place by a third arc surface. The bronze is left with a sharp corner at the entry side so as to limit definitely the thickness of the oil film.

As members are aware, nitralloy steel is nitrided at a temperature of only 500° which is well below any temperature of structural change in the steel. The nitrided case is of a hardness of about 1100 brinell. The structure of the case is extremely firm and is quite free from the danger of surface cracking. Moreover, no distortion occurs as a result of ageing in use, or while heating up. The result is that these spindles can be used with much less bearing clearance than the older type required. In practice the oil film can be cut down to the minimum leaving only the thin film that cannot be squeezed out by any ordinary loads. As the pressure on top of the spindle can be adjusted easily at any time by the fingers, the operator can ensure a dead steady spindle without the slightest fear of seizure. It is this great improvement in running conditions that makes it so much easier to obtain a good finish and freedom from chatter.

The tests proved that in the older type of construction the wheel spindle floating in its thickly oil-lined bore was free to vibrate as a whole.

It is of interest to note that the sound caused by truing the grinding wheel with a diamond is quite different on the new type spindle and bearing construction as compared with the sound given to the diamond on the older type spindle and bearing. This comparison also gives a clue to the reason why it has been found necessary to use with the new wheelheads, grinding wheels two or three grades softer than previous practice had established. Undoubtedly the continual state of vibration of the spindle in the thick oil film caused the grinding wheel to break up more freely and a misleading impression of a soft free cutting wheel was obtained. With the new wheelhead such a wheel proves too hard in grading, and as softer wheel is necessary to maintain the essential break-up of the wheel surface.

(*At this stage the author showed a series of lantern slides showing examples of grinding practice*).

Centreless Grinding.

Centreless grinding has a field of its own, justifying individual treatment before your Institution. There is insufficient time to refer to more than one or two examples. Centreless grinding is available for parallel work, shouldered work, formed work, and bar grinding. The work is dealt with either by the through feed

method, equivalent to continuous traverse in one direction only, or the infeed method equivalent to plunge cut grinding.

Surface Grinding.

Surface grinding practice is perhaps the one field of grinding which leaves open controversy as to which is more economical—grinding or some other machining method such as milling or planing. The development of hydraulic applications with their resulting high speed of table traverse has, however, placed the vertical spindle surface grinder ahead of all other types so far as production is concerned. High speed hydraulic traverse has increased production by some three times and many more surfacing operations from castings in the black can now be efficiently and cheaply dealt with in the reciprocating table vertical spindle grinding machine, instead of by milling or planing. The vertical spindle surface grinder is in many senses a universal machine. Any work that can be held conveniently on a magnetic chuck or by simple clamps can be dealt with more quickly than on any other type of machine, and besides removing the material quickly an accuracy in flatness is obtained that is far ahead of milling or planing.

Economy of Grinding.

At one time it was usual to consider the grinding operation from the point of view of cost as compared with other machining methods. To-day, fully 90 per cent. of work finished by grinding could not be dealt with by any other method. In other words, grinding practice has had a tremendous effect on design, enabling hardened parts to be used extensively.

When the parts of present-day motor car engine and transmission are considered it is evident what a very big effect the precision grinding machine has had on development. Without grinding the present-day motor car engine would never have been possible. In this way the grinding machine has opened up an entirely new range of operations and in such cases it is not a question of considering alternatives to grinding since no alternatives are available.

Grinding operations, therefore, can be roughly classified as those in which alternative machining or hand operations have previously been used, and operations which have only been possible commercially since the development of grinding.

British, American and German Practice Compared.

Although the simplest early types of grinding machine were produced in this country, these machines used wheels composed of natural abrasives. With the manufacture of artificial abrasives some 30 or 40 years ago, great developments in precision grinding took place in this country and in America. In this country it has been essential to study the design of grinding machines more from

the point of view of general engineering. With their wide market, the American grinding machine makers have been able to develop along well-marked lines, and specialisation in certain types of machines have been very marked.

One of the results has been that American makers have produced some highly specialised machines of which there are no real counterparts in this country. In America such machines have found a comparatively ready market, but a number of firms in this country who could economically instal such machines have been very few and far between. While American firms specialising on the manufacture of a few articles have been able to manufacture similar parts in hundreds of thousands, our manufacturers have generally been satisfied to deal with thousands, and these relative conditions have had a very great effect on the designs of the precision grinding machines produced in the two countries.

In the years following the War a tendency with American grinding machine makers has been to increase continually the general massiveness of their machines, and this tendency has been particularly noticeable in plain grinding machines.

As mentioned previously in this paper, the adoption of hydraulic traverse meant at first an all-round increase of weight. These heavy machines have been installed not only for heavy duty work but for light work as well.

In the last year, however, there appears to have been a full swing of the pendulum in the other direction because to-day there is no market for these heavy expensive machines, and new models of American plain grinders are being offered with grinding wheel speeds, grinding wheel diameters, and other details, surprisingly small in view of the calibre of the previous models.

German machine tool makers approached grinding from an entirely different point of view. They did not consider the grinding machine as a production machine but rather as a precision lapping machine. The result of this view point is to be seen in nearly all the products of the grinding machines built in Germany. The h.p. of motors recommended for different types of machines are in general considerably lower than those of American or British recommendations for machines of similar capacity. In vertical spindle surface grinding machines a type of machine with a greater metal removal capacity than any other grinding machine—the h.p. capacities of German machines are generally not more than half of those recommended by other makers. Many of the machines from Germany, however, are marked by great originality in design and the application of novel features.

In conclusion the author would like to make a plea for more co-operation between the grinding machine maker and the user. Practically every development in grinding machines, as in other

machine tools, has arisen out of the needs of the user. The designer comes in after the user has put his cards on the table and has fully informed the machine builder of his difficulties and any unsuccessful steps that may have been taken.

It appears unreasonable for the manufacturer to submit merely a drawing of the component to be ground, and in effect say to the grinding machine builder, " Supply me with a machine to grind this part. I am not telling you what production I want ; what difficulties I have previously encountered in dealing with this work, or anything about my present methods." He says to the grinding machine maker, " You must start from the beginning every time irrespective of what has been done before." Such an attitude happily is not universal among manufacturers, but it is still sufficiently in evidence to slow up a great deal of development. In such cases the grinding machine maker must offer a machine to perform a certain operation, and generally he is kept in the dark as to the production requirements that are necessary. At the same time the machine tool maker is expected to shoulder every risk and accept all responsibility for the satisfactory operation of the machine. Certain well-known machine tool users in this country, however, have shown a much wider outlook and it is to be hoped that such willingness to co-operate will extend rapidly.

er
y
al

a
e
d
t
s
e
y
e
ll
.
o
k
e
d
e
,
d